

# Accurate X-ray position and multiwavelength observations of the isolated neutron star RBS 1774

N. Rea<sup>1,2\*</sup>, M.A.P. Torres<sup>3</sup>, P.G. Jonker<sup>1,3,4</sup>, R.P. Mignani<sup>5</sup>, S. Zane<sup>5</sup>, M. Burgay<sup>6</sup>, D.L. Kaplan<sup>7</sup>, R. Turolla<sup>8,5</sup>, G.L. Israel<sup>9</sup>, D. Steeghs<sup>3</sup>

<sup>1</sup>*SRON Netherlands Institute for Space Research, Sorbonnelaan, 2, 3584CA, Utrecht, The Netherlands*

<sup>2</sup>*School of Physics, A29, University of Sydney, NSW 2006, Australia*

<sup>3</sup>*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

<sup>4</sup>*Astronomical Institute, Utrecht University, PO Box 80000, 3508 TA, Utrecht, The Netherlands*

<sup>5</sup>*Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking Surrey, RH5 6NT, UK*

<sup>6</sup>*INAF–Astronomical Observatory of Cagliari, Loc. Poggio dei Pini, Strada 54, 09012 Capoterra (CA), Italy*

<sup>7</sup>*Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

<sup>8</sup>*Department of Physics, University of Padua, via Marzolo 8, I-35131, Padova, Italy*

<sup>9</sup>*INAF–Astronomical Observatory of Rome, via Frascati 33, 00040, Monteporzio Catone (RM), Italy*

5 February 2008

## ABSTRACT

We report on X-ray, optical, infrared and radio observations of the X-ray dim isolated neutron star (XDINS) 1RXS J214303.7+065419 (also known as RBS 1774). The X-ray observation was performed with the High Resolution Camera on board of the *Chandra* X-ray Observatory, allowing us to derive the most accurate position for this source ( $\alpha = 21^{\text{h}}43^{\text{m}}3^{\text{s}}.38$ ,  $\delta = +6^{\circ}54'17''.53$ ; 90% uncertainty of  $0''.6$ ). Furthermore, we confirmed with a higher spatial accuracy the point-like nature of this X-ray source. Optical and infrared observations were taken in B, V,  $r'$ ,  $i'$ , J, H and K<sub>s</sub> filters using the Keck, VLT, Blanco and Magellan telescopes, while radio observations were obtained from the ATNF Parkes single dish at 2.9 GHz and 708 MHz. No plausible optical and/or infrared counterpart for RBS 1774 was detected within the refined sub-arcsecond *Chandra* X-ray error circle. Present upper limits to the optical and infrared magnitudes are  $r' > 25.7$  and  $J > 22.6$  ( $5\sigma$  confidence level). Radio observations did not show evidence for radio pulsations down to a luminosity at 1.4 GHz of  $L < 0.02 \text{ mJy kpc}^2$ , the deepest limit up to date for any XDINS, and lower than what expected for the majority of radio pulsars. We can hence conclude that, if RBS 1774 is active as radio pulsar, its non detection is more probably due to a geometrical bias rather than to a luminosity bias. Furthermore, no convincing evidence for RRAT-like radio bursts have been found. Our results on RBS 1774 are discussed and compared with the known properties of other thermally emitting neutron stars and of the radio pulsar population.

**Key words:** stars: pulsars: general — pulsar: individual: RBS 1774

## 1 INTRODUCTION

Over the last decade, thank to the high sensitivity of *ROSAT* in the soft X-ray band (0.1–2 keV), a number of thermally emitting X-ray pulsars have been discovered, commonly called X-ray dim isolated neutron star (XDINSs). To date, seven such sources are known: RX J1856.5–3754, RX J0720.4–3125, RX J0420.0–5022, RX J0806.4–4123, RX J1308.6+2127, RX J1605.3+3249

and 1RXS J214303.7+065419 (see Haberl 2007 and van Kerkwijk & Kaplan 2007 for recent reviews).

There is now consensus that XDINSs are nearby, middle-aged ( $\approx 10^6$  yr), cooling neutron stars. Their properties are, however, at variance with those of radio pulsars, and with those of other classes of isolated neutron stars detected at X-ray energies. In particular, i) their spectra are purely thermal, with no evidence for a power-law tail extending to higher energies; ii) their spin periods cluster in a rather restricted range ( $\sim 3$ –11 s) and are much longer than those typical of radio pulsars (similar, however, to those of the

\* E-mail: N.Rea@sron.nl

<u>Instrument</u>	<u>Date (UT)</u>	<u>Exposure (ks)</u>	<u>Band</u>	<u>Pixel Size (")</u>
<i>Chandra</i> HRC-I	2006-07-20	9.7	0.3–8 keV	0.131
			<u>Filter</u>	<u>Seeing (")</u>
Keck	2001-09-21	2.06	B	0.5
Blanco	2006-06-29	2.4	r'	1.1–1.2
	2006-06-29	1.44	i'	1.1–1.2
VLT	2005-08-31	3.0	V	1.5
	2003-11/2004-01	2.6	H	0.6–0.9
Magellan	2006-08-6,10,13	9.0	J	0.5
	2006-08-6,7,8	9.72	K <sub>s</sub>	1
			<u><math>\nu</math> (MHz)</u>	<u><math>\Delta\nu</math> &amp; <math>\delta\nu</math> (MHz)</u>
Parkes	2006-04-20	12.96	2935.5	576.0 , 3.0
	2006-04-20	12.96	708.875	64.0 , 0.25

**Table 1.** Log of the observations.

magnetar candidates, namely the Anomalous X-ray Pulsars (AXPs) and the Soft Gamma-Repeaters (SGRs), e.g. Woods & Thompson 2006); and iii) no evidence for radio emission has been reported so far despite deep searches (Brazier & Johnson 1999; Johnston 2003; Kaplan et al. 2003; Burgay et al. 2007, in prep). Recently, pulsed emission from two sources have been claimed at very low frequencies (Malofeev et al. 2005, 2007), but this has not been confirmed yet .

The low values of the column density derived from X-ray data ( $N_H \approx 10^{20} \text{ cm}^{-2}$ ) indicate that XDINSs have a typical distance of a few hundred parsecs (see e.g. Posselt et al. 2007). The overall X-ray spectrum of XDINS is remarkably well reproduced by an absorbed blackbody with temperatures in the range  $kT \sim 40\text{--}100 \text{ eV}$ . Application of more sophisticated, and physically motivated, models for the surface emission (atmospheric models in particular) result in worse agreement with the data. Furthermore, *XMM-Newton* and *Chandra* observations have shown that in all XDINS spectra, except RX J1856.5-3754, broad ( $EW \approx 10\text{--}100 \text{ eV}$ ) absorption features are present at energies of several hundred eVs. The most likely interpretations are that they are due to proton cyclotron (at the fundamental resonance) and/or bound-free, bound-bound transitions in H, H-like and He-like atoms in the presence of a relatively high magnetic field  $B \approx 10^{13}\text{--}10^{14} \text{ G}$ .

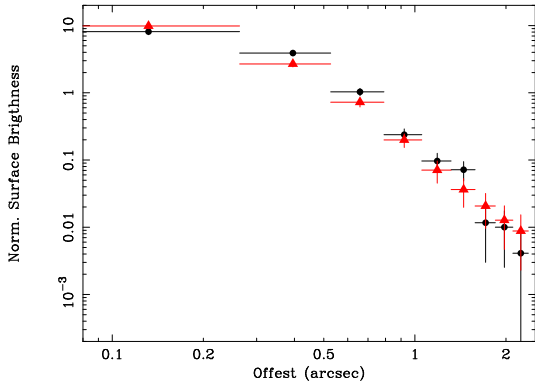
The detection of an optical counterpart is fundamental in XDINS science, because it paves the way to the measure of the neutron star proper motion (as in RX J1856.5-3754, Walter 2001, Neuhäuser 2001; RX J0720.4-3125, Motch et al. 2003; RX J1605.3+3249, Motch et al. 2005, Zane et al. 2006), and of the parallax, as in RX J1856.5-3754 (Walter & Lattimer 2002, van Kerkwijk & Kaplan 2007) and RX J0720.4-3125 (Kaplan et al. 2007). The knowledge of the distance, coupled with X-ray data, may provide tight constraints on the star radius allowing to test the equation of state of the matter at supra-nuclear densities. Furthermore, because of the emission coming directly from the star surface, XDINSs offer an unprecedented opportunity to investigate the thermal and magnetic distributions of isolated neutron stars. Up to now, however, no self-consistent model can properly ac-

count for the multiwavelength spectral energy distribution (SED) of XDINSs, despite some recent progresses (e.g. Pons 2002; Turolla et al. 2004; Geppert et al. 2006; Zane & Turolla 2006; Pérez-Azorin et al. 2006; Ho et al. 2007).

1RXS J214303.7+065419 (RBS 1774) was identified in the *ROSAT* Bright Source catalogue at about  $48'$  from the BL Lac MSS 2143.4+0704 (Zampieri et al. 2001). Despite the limited statistics, this first *ROSAT* PSPC observation was enough to reveal the thermal character of the X-ray spectrum ( $kT \sim 92 \text{ eV}$ ). This, together with a lower limit of  $\sim 1000$  obtained for the optical-to-X-ray flux ratio, fully qualified RBS 1774 as a XDINS candidate. A subsequent *XMM-Newton* pointed observation confirmed RBS 1774 as a member of the XDINS class and revealed a spin period of  $\sim 9.437 \text{ s}$  with a pulsed fraction of  $\sim 4\%$  (Zane et al. 2005). Similar to other XDINS, the *XMM-Newton* spectrum of RBS 1774 is well fitted by an absorbed blackbody ( $N_H \sim 3.65 \times 10^{20} \text{ cm}^{-2}$ ,  $kT \sim 104 \text{ eV}$ ) plus an absorption edge at  $E_{\text{edge}} \sim 694 \text{ eV}$  (see Zane et al. 2005, Cropper et al. 2007 for further details). The  $0.2\text{--}2 \text{ keV}$  unabsorbed flux was  $\sim 5 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ .

Optical follow up with the New Technology Telescope (NTT) in La Silla (Chile), revealed many sources in the *ROSAT* error circle (see tab. 2 in Zampieri et al. 2001) up to a limiting magnitude of  $R \sim 22.8$ . However, the large *ROSAT* RBS 1774 position uncertainty prevented to reliably accept or reject any candidate, except the brightest ones, the color of which were inconsistent with being the counterpart of an isolated neutron star. In the smaller *XMM-Newton* error circle no optical counterpart was found in the NTT exposure (Zane et al. 2005). More recently, Mignani et al. (2007) reported on *VLT* observations that revealed no source in the *XMM-Newton* error box, down to a limiting magnitude of  $V \sim 25.5$ .

We report in §2.1 on the accurate X-ray position of RBS 1774 obtained with the Imaging detector of the High Resolution Camera (HRC-I) on board of the *Chandra* X-ray Observatory. In §2.2 we show optical and infrared observations of the field around RBS 1774, and in §2.3 we present deep radio observations taken with the ATNF Parkes single



**Figure 1.** *Chandra* HRC-I RBS 1774 2D profile (filled circles) superimposed with the simulated instrumental PSF (filled triangles).

dish antenna<sup>1</sup>. We then present our results in §3, and discuss our findings in §4 in comparison with those observed in other thermally emitting neutron stars.

## 2 OBSERVATIONS

### 2.1 X-ray observation: *Chandra*

The *Chandra* High Resolution Imaging Camera (HRC-I; Zombeck et al. 1995) observed the XDINS RBS 1774 on 2006 November 26th, for an on-source exposure time of  $\sim 1.1$  ks. The target was detected  $0''.32$  off-axis with respect to the standard aim-point. Data were reduced with CIAO 3.4 software<sup>2</sup> and analysed with standard software packages for X-ray data (*Ximage* and *Xronos*). We first checked the data for the presence of solar flares and extracted a new observation-specific bad-pixel file. We then run a degap correction, cleaned the image for the hot pixels, and corrected the astrometry for any processing offset.

Only one source was significantly detected in the whole  $30' \times 30'$  HRC-I field of view. We used three detection algorithms: the CIAO *wavedetect* and *celldetect* tools, and the wavelet-based PWDETECT software developed and optimised for *Chandra* images (Damiani et al. 1997). The source has the following coordinates:  $\alpha$  (J2000) =  $21^{\text{h}}43^{\text{m}}3^{\text{s}}.38$ ,  $\delta$  (J2000) =  $+6^{\circ}54'17''.53$ . The statistical uncertainty in the position was  $0''.18$ . Unfortunately the lack of other sources in the field not allow us to correct for uncertainties in the bore-sight. We therefore took the *Chandra* aspect solution for HRC-I which gives an uncertainty of  $0''.6$  (90% confidence level). The RBS 1774 position was consistent within all the detection algorithms and with the previous *ROSAT* and *XMM-Newton* error circles (Zampieri et al. 2001; Zane et al. 2005). Finally, the spatial profile was found to be in good agreement with the expected *Chandra* point spread function (PSF) for on-axis source (see Fig. 1).

Photon arrival times were extracted from a circular region with a radius of  $3''$ , including more than 90% of the source photons, and corrected to the barycenter of the Solar System. We collected a total of 325 counts from the source, we then inferred an effective HRC-I countrate of  $0.290 \pm 0.017$  ct s<sup>-1</sup>. Assuming that the RBS 1774 continuum spectrum did not change with respect to the latest *XMM-Newton* observation ( $N_H \sim 3.65 \times 10^{20}$  cm<sup>-2</sup> and kT  $\sim 104$  eV; Zane et al. 2005), we inferred (using *WebPIMMS*<sup>3</sup>) an absorbed 0.2–2 keV flux of  $2.6 \times 10^{-12}$  erg s<sup>-1</sup> cm<sup>-2</sup>, which translates to an unabsorbed flux of  $4.7 \times 10^{-12}$  erg s<sup>-1</sup> cm<sup>-2</sup>. This flux is consistent with the source having remained stable.

Despite the very accurate timing resolution of the HRC-I camera, no pulsations at the period of  $\sim 9.4$  s (or any other period) were detected, due to the low number of counts. In fact, no pulsations at the predicted spin period would had been detectable unless having a pulsed fraction  $> 80\%$ . RBS 1774 pulsed fraction is 4%, well below this limit.

### 2.2 Optical and infrared observations:

*Keck, VLT, Blanco and Magellan*

Optical and infrared images of RBS 1774 were taken in the *B*, *V*, *r'*, *i'*, *J*, *H* and *K<sub>s</sub>* bands (see Tab. 1 for the log of the observations and Fig. 2 for the finding chart).

Images in the *B*-band were obtained on 2001 September 21 using the LRIS instrument (Oke et al. 1995) mounted on the Keck I telescope at the W.M. Keck Observatory in Hawaii. The field was observed in the *B*-band for a total exposure of 2060 s. The night was not photometric whereas the seeing was  $0''.5$ . The data were corrected for bias and flat field in the usual way using *IRAF*<sup>4</sup>. The photometric zero-point was determined for the combined frame by measuring 10 stars well-detected in both the combined frame and the 60-s frame (we could not use the same zero-point for both due to transparency variations), and checked by directly measuring 4 USNO B1.0 stars in the field in RBS 1774 that were not saturated in our stacked image. We estimate an uncertainty of 0.5 magnitudes in the zero-point.

On 2006 June 29 we observed the RBS 1774 field with the *r'* and *i'* Sloan filters using the MOSAIC-II instrument mounted at the 4 m Blanco telescope at the Cerro Tololo Inter-American Observatory. We observed the field for 2400 s in *r'* and 1440 s in *i'* (see also Tab. 1). The data were corrected for bias and flat field in the usual way using the *MIDAS* software<sup>5</sup>. The night was photometric and the seeing was  $1''.1$ – $1''.2$ . The frames were calibrated with respect to the standard star SA 107 using the SDSS DR5 magnitudes of that field (Adelman-McCarthy et al. 2007 submitted). We estimated an error of 0.3 magnitudes in our zero-point.

RBS 1774 was subsequently observed in the *V* and *H*-bands from the VLT at Paranal Observatory in Chile using *FORS1* (FOcal Reducer Spectrograph) and *ISAAC* (Infrared Spectrometer And Array Camera), respectively. *FORS1* was operated in its standard resolution mode (pixel size  $0''.2$ ; field of view  $6''.8 \times 6''.8$ ). Out of the original program approved

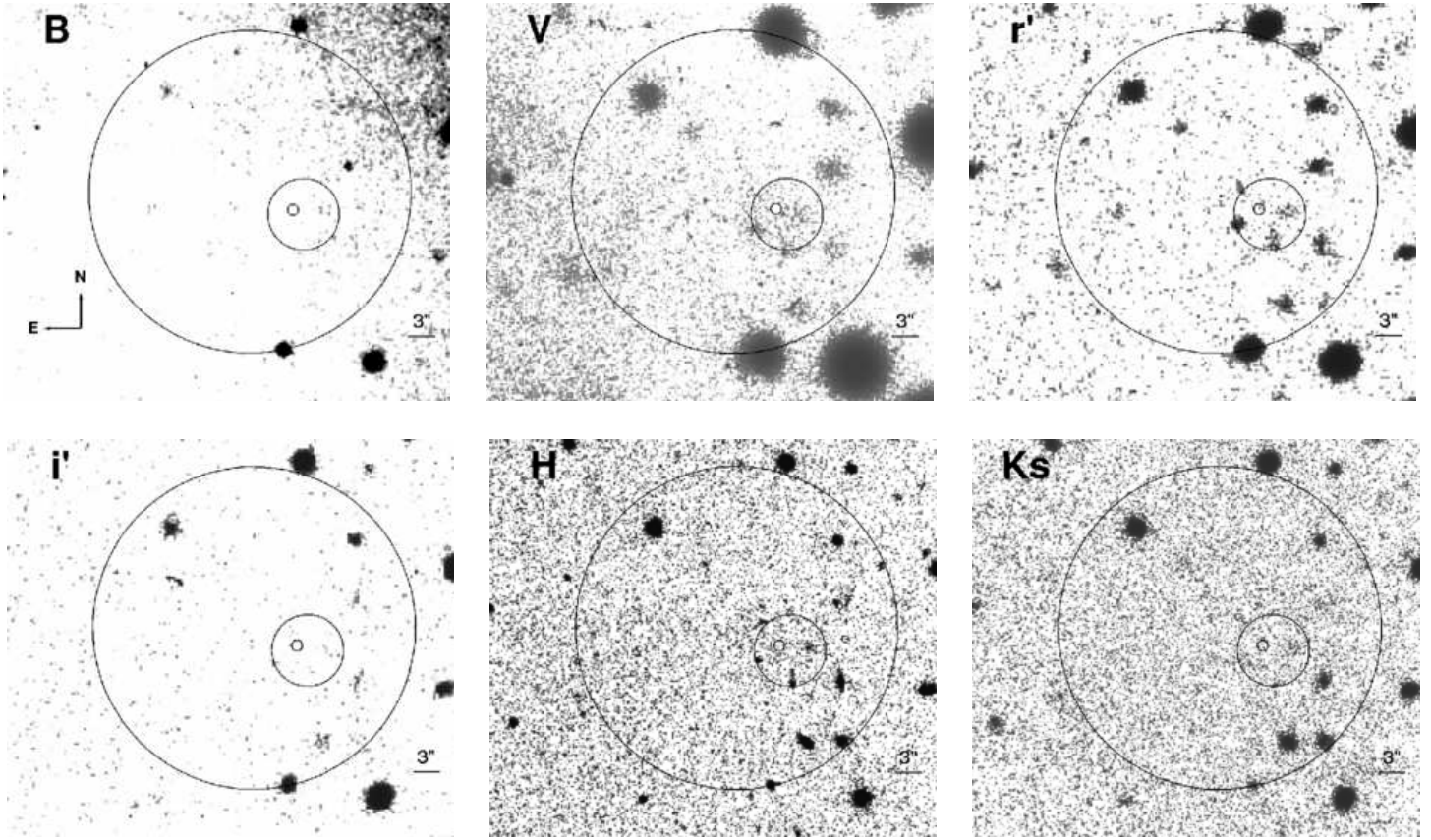
<sup>1</sup> Through this paper we assumed for RBS 1774 a distance of 400 pc, based on  $N_H$  measurements from Posselt et al. (2007). However, our results will need to be scaled if a more exact measurement of the distance will become available.

<sup>2</sup> <http://asc.harvard.edu/ciao/>

<sup>3</sup> <http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms>

<sup>4</sup> <http://iraf.noao.edu/>

<sup>5</sup> <http://www.eso.org/projects/esomidas/>



**Figure 2.** Optical and infrared fields of RBS 1774 with overplotted the *RASS* (Zampieri et al. 2001), *XMM-Newton* (Zane et al. 2005) and *Chandra* 90% error circles on its position (*RASS* > *XMM-Newton* > *Chandra*). We plotted the histogram of the images and smoothed them with a Gaussian function. From left to right, *first row*: *B*, *V* and *r'* images from Keck, VLT and Blanco, respectively; *second row*: *i'*, *H* and *K<sub>s</sub>* images from Blanco, VLT and Magellan, respectively. North is up and East left for all images. Note that the few black dots within the *Chandra* error circle, are due to hot pixels.

for Service Mode, RBS 1774 was observed in the *V*-band only for about one hour (see also Mignani et al. 2007), and with relatively bad seeing conditions ( $\sim 1''.5$ ). Photometric calibration was ensured by observations of Landolt stars at the beginning of the night. Data reduction (bias subtraction, flat fielding) was performed using the *FORS1* data reduction pipeline. The exposures were combined and cosmic rays hits filtered out. For the *ISAAC* observations in the *H*-band, the Short Wavelength (SW) camera was used, equipped with a Rockwell Hawaii 1024 $\times$ 1024 pixel Hg:Cd:Te array ( $0''.148$  pixel size;  $152\times 152$  arcsec field of view). To allow for sky background subtraction, each exposure was split in sequences of 33 randomly dithered exposures of  $5\times 12$  s each. Night conditions were good ( $0''.6 - 0''.9$  seeing) but not perfectly photometric due to the presence of variable cirrus clouds. Science exposures were retrieved through the public ESO archive<sup>6</sup> together with the closest in time calibration files and reduced using the ESO's eclipse package<sup>7</sup> for de-jitter and sky subtraction. Stacks of images taken in different nights have been co-added. Due to the lack of suitable standard star observations during the nights, for the photometric calibration we have used 2MASS stars identified in

the image. This yielded a photometric calibration accurate within  $\sim 0.3$  magnitudes, also accounting for the photometric accuracy of 2MASS and the passband difference between the 2MASS and the *ISAAC H*-band filters.

Furthermore, we observed RBS 1774 in the *J* and *K<sub>s</sub>*-bands using the PANIC camera on the 6.5-m Baade Magellan Telescope at Las Campanas Observatory (LCO). PANIC (the Persson's Auxiliary Nasmyth Infrared Camera) yields a  $0''.125$  pixel $^{-1}$  plate scale onto a Rockwell Hawaii Hg:Cd:Te 1024 $\times$ 1024 array (Martini et al. 2004). The observations consisted of several 9 point dither patterns with a 20s (*K<sub>s</sub>*) and 60s (*J*) exposure repeated three times at each offset position. The total time expended on source was 2.5 and 2.7 h in the *J* and *K<sub>s</sub>*-bands, respectively. However, weather conditions were variable (with seeing ranging  $0''.5$  and  $1''.2$ ) and we had to reject a significant number of images obtained under bad conditions (poor seeing, clouds and/or variable background) as including them would deteriorate the final photometry. The data were reduced through the PANIC software: the raw frames were first dark subtracted and flat-fielded. Master flat-fields were made by combining 75 (*J*) and 95 (*K<sub>s</sub>*) twilight flat field frames scaled by their mode. Next, a sky image was subtracted from the set of target frames. The sky image was built by masking out stars from each set of dithered frames. Finally, a mosaic image was obtained by combining and averaging the sky-subtracted im-

<sup>6</sup> <http://archive.eso.org/>

<sup>7</sup> <http://www.eso.org/projects/aot/eclipse/eug/eug/eug.html>

ages. For the analysis we used mosaic images generated by stacking the frames with better seeing and not affected by variable weather. The total on-source time for these mosaic frames was 54 and 108 min, with a seeing of  $0''.5$  and  $1''$  for  $J$  and  $K_s$ , respectively. Absolute calibration of the  $J$ -band data set was performed using the standard star S301-D (Persson et al. 1998), observed the same night the RBS 1774  $J$  image was obtained, and assuming a median extinction value of  $= 0.092 \text{ mag airmass}^{-1}$  (Nikolaev et al. 2000). We estimate a systematic error  $< 0.2 \text{ mag}$  for the photometric zero point. Absolute magnitude calibration for the  $K_s$ -band was performed using three 2MASS stars contained in the  $2 \times 2 \text{ arcmin}$  PANIC field of view. Note that the LCO photometric system yields a  $K_s$ -band magnitude that is the same within the photometric errors to that obtained with 2MASS (see e.g. Carpenter 2001).

### 2.2.1 Astrometry

An absolute astrometry was derived by tying all the images to the 2MASS catalogue. First, we established a plate solution for the *FORS1* V-band image using the *IRAF* tasks *ccmap* and *cctran* on fourteen 2MASS reference stars. The *rms* residuals of the astrometric fit were  $< 0''.1$ . Next we measured the positions of ten foreground stars in the *FORS1* image that were close to RBS 1774. This secondary grid of reference stars was necessary due to the smaller field of view covered by *ISAAC* and *PANIC*, and because some of the above primary references are saturated in the Blanco and Keck frames. After accounting for all the errors of our astrometric chain and for the intrinsic absolute astrometric accuracy of 2MASS (Skrutskie et al. 2006), we end up with an overall uncertainty of  $< 0''.23$  on the absolute astrometry.

### 2.3 Radio observations: ATNF Parkes

RBS 1774 was observed in radio with the dual-band coaxial 10-50cm receiver of the Parkes radio telescope in 2006 April 13th. The observations was carried out at 2.9 GHz and 708 MHz (10 cm and 50 cm, respectively) simultaneously, for a total of 3.6 hrs and data have been one bit sampled every 0.215 ms (Burgay et al. 2007, in prep).

Data analysis was done with *vlssa* (e.g. Burgay 2000), a code using a standard FFT based periodicity search algorithm. The data have been dedispersed with different trial values of the dispersion measure (DM) ranging from 0 to 200; the range adopted is very conservative since, assuming for RBS 1774 a distance of 400 pc (Posselt et al. 2007), the predicted Galactic DM is  $< 10 \text{ pc cm}^{-3}$  (Taylor & Cordes 1993; Cordes & Lazio 2002).

No clear signal (having signal-to-noise ratio  $S/N > 8$ ) was found around the spin period detected in X-rays (Zane et al. 2005) nor at any period ranging from 1 ms to 10 s. The sensitivity limits of this search can be calculated using the radiometer equation (see Manchester et al. 2001) with the following parameters:  $T_{\text{sys}}$  equal to 30 and 40 K,  $G$  equal to 0.67 and 0.59 K/Jy, for the 2.9 GHz and 708 MHz observation respectively.

For a pulsar with period  $P=9.437 \text{ s}$  and a duty-cycle of  $< 5\%$  we obtain a flux density limit  $S_{\text{min}} < 0.33 \text{ mJy}$  for the observations at 708 MHz and  $S_{\text{min}} < 0.06 \text{ mJy}$  for the observation at 2.9 GHz.

B	V	r'	i'	J	H	K <sub>s</sub>	2.9 GHz	708 MHz
24.0	25.5	25.7	24.2	22.6	21.9	20.8	0.33	0.06

**Table 2.** *Upper row:* observing bands. *Lower row:* Optical/infrared magnitude and radio flux  $5\sigma$  upper limits of the counterpart to the XDINS RBS 1774. Radio flux upper limits refers to pulsed emission and are in unit of mJy (Burgay et al. 2007, in prep).

## 3 RESULTS

Thanks to the *Chandra* high spatial accuracy, we inferred a  $0''.6$  accurate position for RBS 1774 (see §2.1), crucial to search for a possible optical/infrared counterpart (see also Fig. 2). Furthermore, studying the *Chandra* PSF we confirmed with a higher accuracy the point-like nature of this source.

We have used our improved *Chandra* position to search for the optical/infrared counterpart to RBS 1774. Unfortunately our images were not deep enough to detect any optical or infrared counterpart (see Fig. 2 and the discussion section for details). The four objects identified close to the *Chandra* position (see Fig. 2) have been already considered unlikely candidates by Mignani et al. (2007) on the base of their  $B - V > 0$ , and of their relatively high optical brightness. Furthermore, two of the objects look extended and are probably extra-galactic background sources.

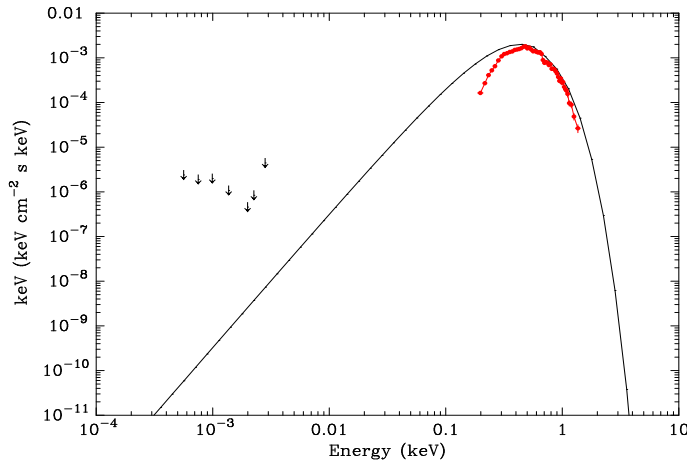
Note that XDINSs are characterised by high proper motions, hence observations too far in time from our *Chandra* observation might make a possible optical/infrared counterpart lie out of the *Chandra* positional error circle. However, except for the Keck observation, all of our observations were close enough to the *Chandra* pointing not to suffer from this effect.

We report in Tab. 2 the  $5\sigma$  upper limits on our non-detections for each band. These limits were derived for each filter from the magnitude of faintest stars detected at  $5\sigma$  confidence level among the stars that fell on the same CCD as RBS 1774. We calculated the reddening in the direction of RBS 1774, from the hydrogen absorption value inferred from the X-ray spectrum ( $N_H = 3.6 \times 10^{20} \text{ cm}^{-2}$ ; Zane et al. 2005), which gives  $E(B - V) = 0.062 \text{ mag}$  (Bohlin, Savage & Drake 1978). We then converted this value into an estimate of the reddening in all the filters we actually used (Cardelli, Clayton & Mathis 1989).

The radio observations we report here (see §2.3) are, up to now, the deepest available for this source and for XDINSs in general (Burgay et al. 2007, in prep), and the obtained radio limits are among the most stringent to date for radio observations of XDINS (see e.g. Kaplan et al. 2003)<sup>8</sup>.

Furthermore, in order to test the hypothesis that XDINS are related to Rotating Radio Transients (RRATs, McLaughlin et al. 2006), a search for single dedispersed pulses (Cordes & McLaughlin 2003) has also been carried out giving negative results. However, the presence of strong

<sup>8</sup> Interestingly, pulsed radio emission from RBS 1774 at  $\sim 110 \text{ MHz}$  was reported by Malofeev et al. (2007). However, this detection still needs a confirmation. We note that our non detection at higher frequency would imply a steep spectrum, with spectral index  $> 2.1$ .



**Figure 3.** Multiband spectrum of RBS 1774. *XMM-Newton* spectrum is plotted, labelled with filled circles (Zane et al. 2005). The solid line shows the unabsorbed blackbody which best fit the X-ray data. The arrows represent our  $5\sigma$  upper limits on the de-reddened optical and infrared flux.

radio frequency interferences do not allow us to give a definite answer on the presence or absence of RRAT-like emission in this source.

#### 4 DISCUSSION AND CONCLUSIONS

We presented the results of a multiband observational campaign of the field of the isolated neutron star RBS 1774. No optical/infrared/radio counterparts have been found (upper limits are reported in Tab. 2 and Fig. 3) within the very small *Chandra* error circle of the source (see § 2.1).

A feature common to all optically identified XDINSs is that their optical flux lies well above the extrapolation of the X-ray blackbody at lower energies (e.g. Kaplan, Kulkarni & van Kerkwijk 2003). This “optical” excess varies from source to source and can be as high as a factor of 10. Whether this is due to emission from regions of the star surface at different temperatures or to other mechanisms, such as non-thermal emission from particles in the star magnetosphere or to a substantial suppression of the crustal emission at X-ray energies (Zane & Turolla 2005, Pérez-Azorín et al. 2006), is still under debate.

Basing on the similarities with the emission of the other optically detected XDINSs (see e.g. van Kerkwijk & Kulkarni 2001; Pons et al. 2002; Kaplan et al. 2003; Ho et al. 2007), RBS 1774 is expected to be quite faint. We show in Fig. 3 the extrapolation of the X-ray spectrum detected by *XMM-Newton* (Zane et al. 2005). Assuming an optical excess as large as a factor 10, the expected magnitudes of RBS 1774 are  $B \sim 28$ ,  $V \sim 28.3$ ,  $J \sim 29.2$ ,  $H \sim 29.3$  and  $K \sim 30$ . Therefore, although the limits presented in this paper are the deepest ones presently available for RBS 1774, they are not deep enough to constrain its optical/infrared spectrum, and in particular the presence of an additional cooler blackbody component which might be responsible for the optical/infrared emission.

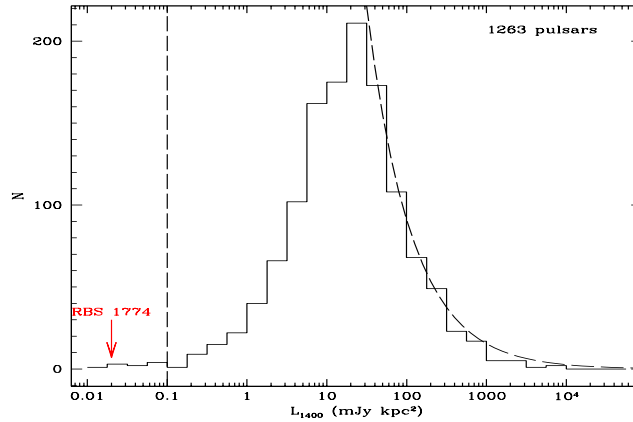
It has been suggested that XDINSs can be related to the magnetars, because of their intriguing similarities in their spin periods and magnetic fields. As proposed in Mignani et al. (2007), a further piece of evidence to relate the two

classes might come from the comparison of their infrared spectra which, in the case of the magnetars, are characterised by a distinctive flattening with respect to the extrapolation of the X-ray spectrum (Israel et al. 2004). If such a flattening is due to a genuine turnover in the neutron star spectrum or due to the presence of a fossil disk, as proposed for the magnetars, the detection of the same effect in both classes would be extremely interesting. In this respect, RBS 1774 looks particularly promising. By interpreting the broad spectral feature observed at  $\sim 0.7$  keV either as a proton cyclotron resonance or bound-bound, bound-free transitions in H or He-like atoms, it requires a magnetar-like magnetic field,  $B \sim 10^{14}$  G, the highest among XDINSs. A systematic search for infrared emission from nearly all XDINSs, including RBS 1774, did not show any evidence for a spectral turnover redward of the *R* band (Lo Curto et al. 2007). Our multiwavelength campaign also shows no signs for such a turnover. Taking as a reference the SEDs of RX J0720.4–3125 (Kaplan et al. 2003) and RX J1856–3754 (Pons et al. 2002; Ho et al. 2007) and using the same X-ray-to-optical normalisation (e.g. Mignani et al. 2007), such a spectral flattening would imply  $H \geq 25$  for RBS 1774.

The radio observations we performed (see § 2.3) gave us very stringent limits, among the most stringent to date for radio observations of XDINS. Assuming a distance of 400 pc and a typical spectral index for long period pulsars of 1.7 (e.g. Kramer et al. 1998) we obtain a luminosity limit at 1400 MHz  $L_{1400} < 0.02$  mJy kpc<sup>2</sup>, lower than what expected for the majority of radio pulsars, for which the most recently derived luminosity function (Lorimer et al. 2006) has a lower limit of 0.1 mJy kpc<sup>2</sup>. A comparison with the luminosity at 1.4 GHz of the known population of pulsars also shows that our limits are very stringent (see Fig. 4), including 99.8% of all known non-recycled galactic field pulsars.

From the above considerations we can hence conclude that, if RBS 1774 is active as radio pulsar, its non detection is more probably due to a geometrical bias (i.e. the radio beam not pointing toward us) than to a luminosity bias. If the pulse duty-cycle is, as assumed above, 5%, the radio beam semi-aperture is  $\geq 9^\circ$ , implying that the probability of an unfavourable geometry is  $\leq 98\%$ . Note that, if the





**Figure 4.** Distribution in luminosity at 1400 MHz of the observed pulsar population of the galactic field. The dashed curve is the radio pulsar's luminosity function (Lorimer et al. 2006). The arrow indicates the luminosity limit reached in the present search.

radio beam is smaller, as suggested by the empirical law by Rankin (1993), the geometrical bias is even worse but our flux limits become even more stringent: for a duty-cycle of 1%, for instance, the limits at 2.9 GHz and 708 MHz are, respectively, 0.03 mJy and 0.14 mJy.

Considering the importance of such studies, future deeper optical/infrared/radio observations of RBS 1774 (and other XDINSs) should be carried out to pinpoint its very faint counterparts. The knowledge of the *Chandra* accurate position we report here, will play a crucial role in the counterpart identification.

## ACKNOWLEDGEMENTS

We acknowledge the director of the *Chandra* X-ray Observatory, Harvey Tananbaum, for according us the RBS 1774 observation through its Director Discretionary Time. These results are based on observations collected at the European Southern Observatory, Paranal, Chile under programme ID 71.C-0189(A), 075.D-0333(A), as well as data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile. Part of the data presented here were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. NR is supported by the Netherlands Organisation for Scientific Research (NWO) through a Post-doctoral Fellowship and a Short Term Visiting Fellowship of the University of Sydney, and thanks the IoA of the University of Sydney for the warm hospitality. MAPT is supported in part by NASA LTSA grant NAG5-10889, PGJ acknowledges support from the NWO, SZ thanks PPARC for financial support through an Advanced Fellowship, and DS acknowledges a Smithsonian Astrophysical Observatory Clay Fellowship as well as support through the NASA Guest Observer program. We thank M. McLaughlin, S. Popov and A. Possenti for according us permission to publish the Parkes data. We thank the referee, Fred Walter, for useful suggestions.

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